Applying the 3-layer approach to urban flood management

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Abstract

Purpose – The purpose of this paper is to find the possibility of extending the capacity of urban drainage in highly urbanized cities with limited available space for flood management, while the anticipated increase in extreme rainfall is expected to raise the demand for higher capacity of water drainage or storage systems.

Design/methodology/approach – The concept of the three-layer approach is introduced to identify the crucial factors which had impacted the historical change of natural water system. These factors can further help identifying potential spaces for new designs of flood management based on the spatial context of local history.

Findings – In Pingtung case, a roadway surface drainage design is found as a complementary strategy by this method, which could effectively and practically extend the capacity of urban drainage without the need for requisitioning private lands or rearranging the complicated underground pipe and cable systems.

Research limitations/implications – This is an initial exploration from the perspective of urbanism to respond to hydrological problems under the impact of extreme rainfall. The more precise hydrologic simulation need to be further established.

Practical implications – This concept could be applied in delta cities to improve urban drainage by three steps: first, clarify the flooding problems; second, identify the available space; third, redesign hydrologic instrument with a multi-use of urban space.

Originality/value – This research provides hydrologists and urban planners with a practical collaboration base for the issues of extreme storm events.

Keywords Manmade disaster, Delta urbanism, Flood management, Layer approach, Storm water, Urban drainage

Paper type Research paper

1. Introduction

1.1 Problem statement

The frequency of disasters, and their effects on population and resulting economic losses, has risen dramatically since 1970. Particularly in recent years, the occurrence of extreme catastrophic events has increased significantly. Hydro-meteorological damages have been the major factor to cause such disaster (Guha-Sapir *et al.*, 2012). This situation is worse especially in estuarine delta regions. Deltas, which traditionally had important roles in providing people with fresh water, fertile soil and vast plains in the past, play even more crucial roles today. With the arrival of globalization, deltas now occupy crucial places for shipping networks throughout the world. As a result, numerous people are moving into deltas to pursue more opportunities. Currently, deltas are the areas with the most rapid urbanization (The World Bank, 2009). The intense urbanization which increases the spatial demand for massive population has put a strain on urban space everywhere, including the areas with potential for disaster prevention. Buffer zones against floods have been reduced, in turn locating more economic activities and real estates in flood risk areas. According to the Global Assessment Report on Disaster Reduction (United Nations International Strategy for

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Disaster Reduction Secretariat, 2009), deltas are particularly vulnerable areas exposed to very high disaster risk. How to extend the spatial capacity for flood management has become an urgent issue. But, it is a tough task for current hydrologic theories to find available spaces in highly urbanized areas.

1.2 The hydrologic approach to dealing with storm water

The primary goal of the traditional approach to urban storm water management is to prevent water retention in population areas (De Barry, 2004; Debo and Reese, 2002). However, this results in a fast flow of storm water towards the lower reaches. The increased peak flows induce inundation in other sections of the river catchment. Several additional management models have been developed to complement this traditional model, with the following five as most prominent: conveyance, detention, extended detention, infiltration and water harvesting (Ferguson, 1998). Conveyance is the draining of storm runoff from the ground surface into the sea or rivers mainly through pipe and channel systems. Since the first modern drainage system was built in 1869 (Ferguson, 1998), this concept has developed into the most common approach to deal with urban storm water. Today, this essential concept is increasingly being supported by complementary approaches (Tucci, 2010). Among them, storm water detention aims to slow down the over-land flow of storm water. It addresses the shortcomings of conveyance because it can reduce the peak flow level of the main stream and efficiently minimize downstream flooding (Reese, 2001). It works best when applied across the entire catchment of a river system (Ferguson, 1998). This model can be further improved as the extended detention model by removing pollutants from collected runoff; infiltration tries to store excess storm water underground. Not only can it directly reduce the peak discharge, but also the ground is a good filter for removing pollutants from the water. Water harvesting is to hold and use the rainfall on-site, including a dam, a reservoir, irrigation, or even water tanks on rooftops or in gardens. It has recently gained popularity in modern industrial cities as a fashionable, environmentally friendly solution, for example sponge cities or green roofs (Bunster-Ossa, 2013; Mentens *et al.*, 2006).

The aforementioned concepts have met new challenges under the impacts of climate change. A new paradigm with the more integrated aspect has to be reframed for storm water management. Debo and Reese note the basic issue is the unliveable environment made by urban sprawl. They assert that it can be improved through some combination technologies (Debo and Reese, 2002). Novotny *et al.* (2010) introduce a triple structure, including society, economy and environment, to illustrate their ideal paradigm of integrated water management which requires a more comprehensive approach and a higher level of political cooperation. Comparing the more technological perspective of Debo and Reese's, they provide a broader vision where diverse participants – governments, social movement organizations and private actors – all play a part. But one practical question remains. How to advance such a broad, trans-disciplinary model? The layer approach applied in Dutch provides practical guidance for answering this question.

1.3 The layer approach as a trans-disciplinary framework for flood management

Academic analysis of the layer technique did not appear until 1950 when Tyrwhitt drew four types of maps including relief, hydrology, rock types and soil drainage on transparent paper, and made reference to common control features. These maps were then combined into a single land characteristics map that provided a comprehensive analysis (Tyrwhitt, 1950; Steinitz *et al.*, 1976; McHarg and Steiner, 1998). And then, McHarg reorganized these approaches as a theoretical background by focusing on both natural and manmade attributes in a given site. He first produced individual transparent maps and then, based on the logic of inductive reason, superimposed the maps over each other to create the necessary suitability maps for each land use (McHarg, 1969).

The layer approach was first introduced in the Netherlands as a triplex model including three layers: abiotic, biotic and anthropogenic factors (Kerkstra and Vrijlandt, 1988; Meyer and Nijhuis, 2013) – for illustrating a complex landscape system. It was further adopted in the Framework Model (Casco-concept) to show natural and manmade landscapes as an interactions system which included three major layers including the substratum, the networks and the occupation (De Bruin *et al.*, 1987; Kerkstra and Vrijlandt, 1988; Sijmons, 1991; Nijhuis and Bobbink, 2010). This structure developed into a more comprehensive structure on the Dutch national level as the Dutch layer approach (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (VROM), 2001b; Van Buuren, 2003), which was embodied in Dutch official planning policy, for instance the Fifth Memorandum on Spatial Planning (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (VROM), 2001a) and the Memorandum on Space (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (VROM), 2006). After the serious threats of near flood conditions in 1995 and 1997, the concept of water management in Holland gradually shifted away from a single hydrologic aspect, such as fighting against water, to a more comprehensive approach, such as working together with water (Edelenbos *et al.,* 2013). This three-layer model provided an integrated framework that combined the concerns of urbanism and landscape architecture.

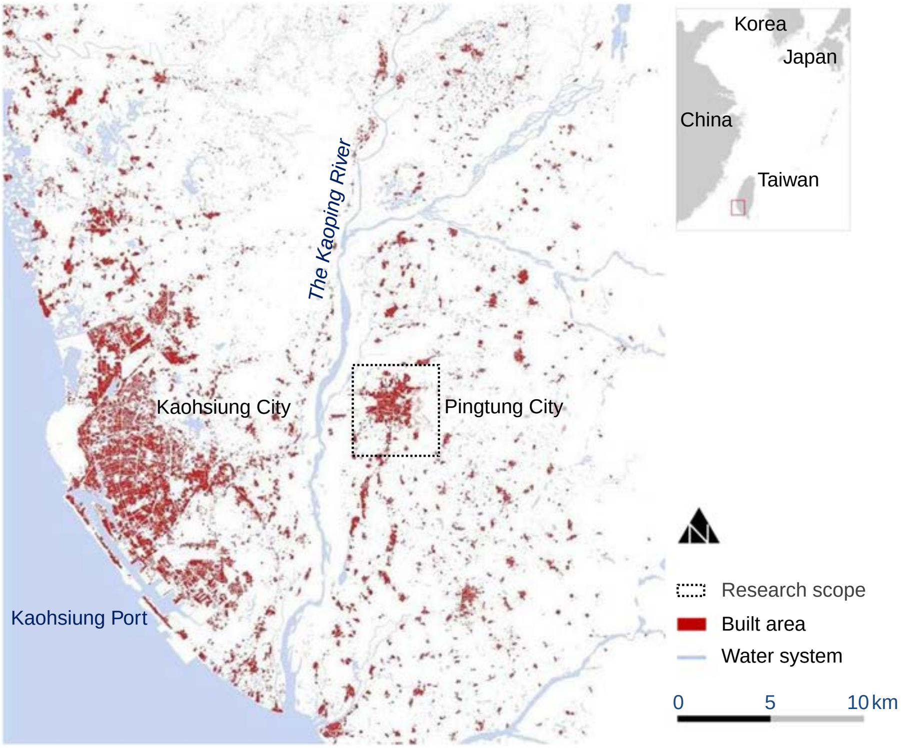
However, these documents use the layer approach without paying more attention to explaining the interrelationship between the different layers (Meyer and Nijhuis, 2013), which is a pity, because this knowledge is helpful for identifying the crucial factors that have the potential to improve environmental quality within a city system. Furthermore, McHarg's inductive reasoning layer approach only compiles information that is already available. Thus, based on the concept of the layer approach, this paper tries to fill this gap by provide a trans-disciplinary framework for exploring interrelationship between the human and the natural landscape, by which additional spatial possibilities for flood management could be uncovered.

2. Method

2.1 Scope

This study focuses on Pingtung City in southern Taiwan, a city under constant threat of flooding. Pingtung is located in the Kaoping River Delta (Figure 1) and has 200,000 inhabitants, with a population density of 3,100 residents per km^2. The average annual rainfall in the Kaoping River catchment is 3,046 mm, which yields 8,455 million cubic metres of annual discharge. Around 69 per cent of the rainfall is concentrated between May and October. The peak discharge usually occurs during the summer typhoon period.

Since the 1990s, the impacts of climate change – especially extreme rainfall – have brought serious challenges to highly urbanized delta cities in Taiwan. In 2010 Typhoon Fanapi caused severe flooding in the Kaoping River Delta; more than 600 mm rainfall



Source: Re-drawn by author; original source from Taiwan DTM, Ministry of Economic Affairs; Academia Sinica (2010)

Figure 1.
The location of Pingtung City and the Kaoping River Delta

accumulated in just six hours. In fact, nine tremendous typhoons hammered Taiwan in the last decade (The Seventh River Management Office, 2011). The high frequency of typhoons with extreme rainfall had caused frequent flooding in and around downtown Pingtung, for instance, in 2006, 2007, 2008 and 2010. All of the schemes proposed after the flood disasters face the problem of space scarcity in the downtown area. A new method is needed to conduct this problem.

2.2 Analytical framework

This paper draws from advances in three domains of knowledge from 1898 to the present: natural landscape, infrastructure and spatial patterns, which are obtained from government reports, plans, records and local histories. The collected geographical information from these three domains is digitally integrated into a basic map in this paper. All of the information is arranged chronologically as a three-layer model. Because the process of rapid urbanization in Taiwan was triggered by Japanese colonization and rapidly increasing after Second World War and then reaching its peak in the 1980s, the situation showed on The Taiwan District Map of 1898 is viewed in this research as the original conditions of the river system.

Furthermore, this study clarifies the transforming context of each layer. Some related effects between different layers are identified in this phase. The maps of current water problems are overlaid on each layer in order to identify possible causes. These possible factors in the different layers are further connected to form a complete mechanism via an analysis of deductive causality. The interrelationship of the natural and human landscapes is illustrated, including identification of the crucial factors and the interactions between these factors. Finally, based on this information, some new possibilities for flood management could be designed.

2.3 Roadway surface drainage as an old/new concept in modern cities

In general, the road drainage system broadly includes all the facilities which can drain runoff from road surface, for instance ditches, culverts, pipes or sub-drainage systems. This research mainly focuses on roadway surface drainage which means the drainage function of road surface. In fact, the concept of roadway surface drainage dates back to Imperial Rome. Although there were fine drainage systems in Roman cities, Roman designed their road systems with draining function in order to flush dirt from streets. Some stepping stones for pedestrian to safely and conveniently cross-streets are still preserved in some heritages locations. This concept obviously fell out of favour with the advent of cars, as keeping the road surface dry and safe for a smooth car ride became the main goal. Gutters and sub-drains system along roads had been the major technology designed after the urban planning, which did not cause serious problems until the impact of extreme rainfall events (Milly *et al.*, 2002; Semadeni-Davies *et al.*, 2008). The changes of natural environment by urban patterns had not only decreased the time to peak discharge but also increased the amount of over-land runoff of storm (Campana and Tucci, 2001). While the drainage capacity is hardly to be extended in a highly urbanized area, the function of roads as a conveyer network for storm water had further been considered.

Concerning the drainage role of street network, Bacchin *et al.* (2011) study eight cities in Asia and Europe on a meso-scale level to evaluate the potential impacts of the urban form on surface drainage performance by a hydro-syntax model. They try to develop a new hydrologic model which could identify flood prone areas in highly urbanized areas. However, this model is especially developed for flat areas which cannot properly explain the flow of storm water in areas with uneven ground, for instance, in Pingtung case. Thus, this research combines the simulation module of SOBEK with the analysis of three-layer to explore the relationship storm water runoff and road network.

3. Results

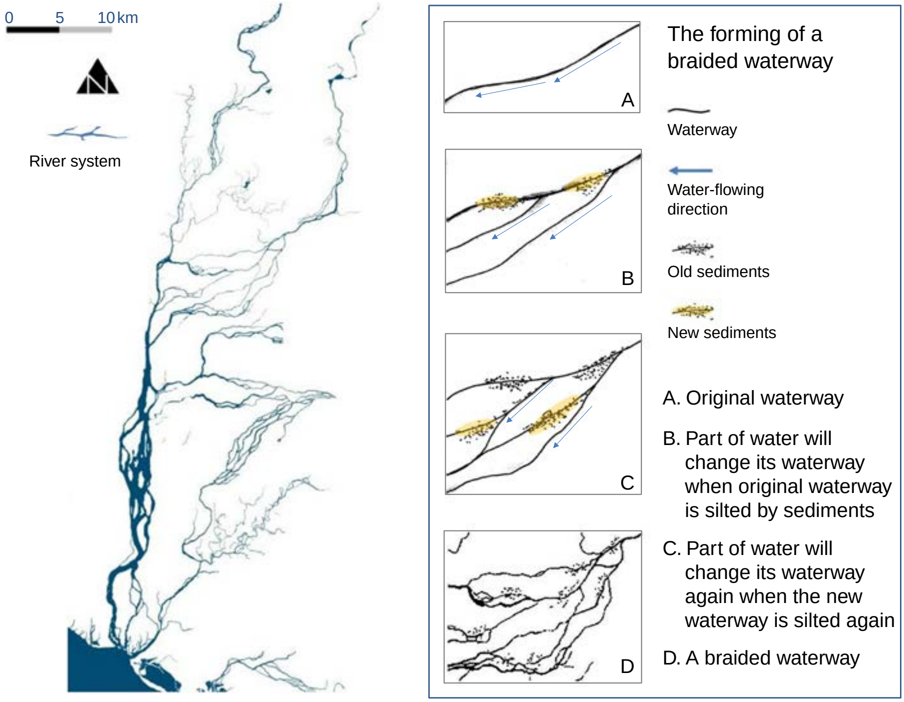
This three-layer model reveals that the manmade landscape had important effect on freshets in downtown Pingtung. The layer examination shows that the natural path of the runoff has been changed substantially in the past 100 years by the dikes and the radial-grid road system, which is the main factor to induce the clogging of storm water in downtown area. The portraits of three layers are as follows.

3.1 The natural river system

The riverbed was changeable in the middle and lower reaches of the Kaoping River, where the water flowed through the mountainous zone into the delta plain, before the completion of the main dike system. Because the terrain of the delta is higher in the northeast than in the southwest, the major waterways ran from the northeast to the southwest. Furthermore, because of huge sedimentation, the riverbed, which contained many sand dunes, was easily clogged. When the original riverbed silted up, partial water, on the one hand, would flush through the silts forming levee deposits along the waterfront. At the same time, part of the water flow would find new southern waterways in which to flow. According to The Japanese Taiwan District Map (Academia Sinica, 2010), this repeated process of silting and changing channels produced a braided channel network in the delta (Figure 2). The map illustrates that this channel network covered most of the delta area, which meant that the most delta plain functioned as a flood plain.

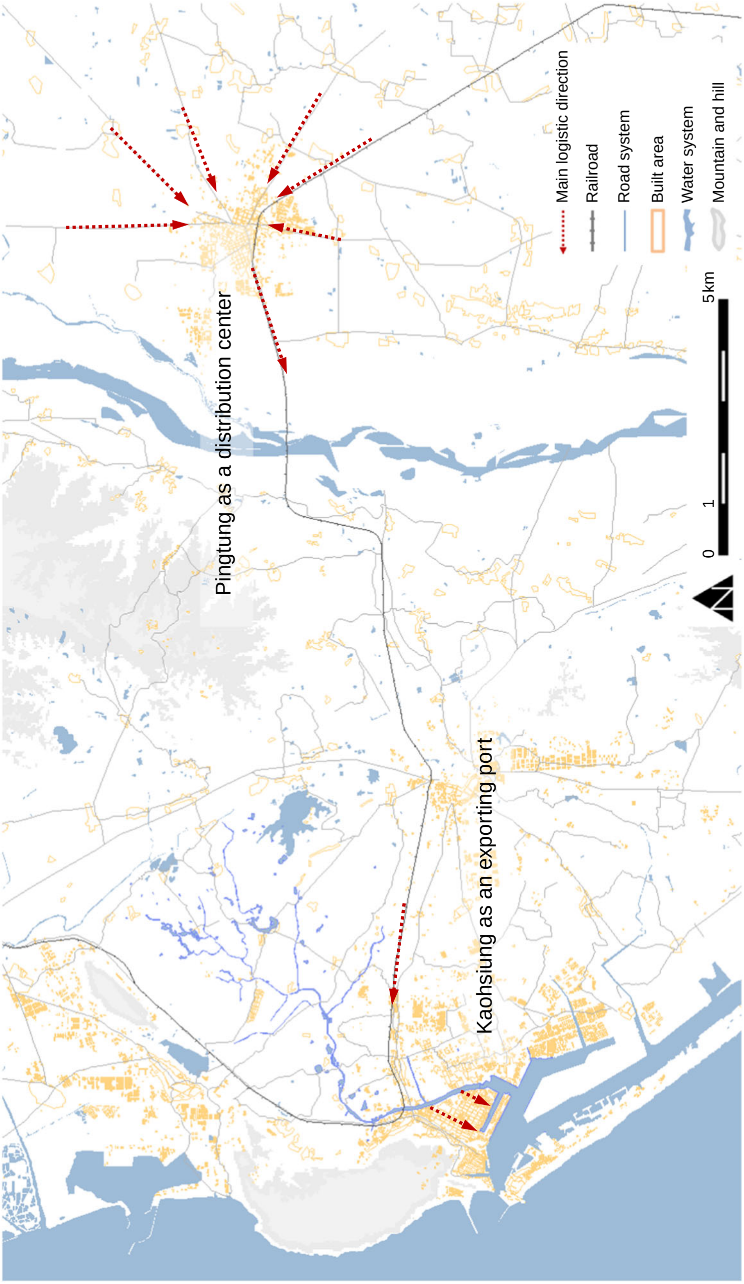
3.2 Infrastructure layer: a twin-core intercity structure

The Japanese viewed Taiwan as an important logistics base for their military in Asia. According to a Japanese survey, Taiwan contributed about 1.5 per cent of the world's sugar output in 1910 (National Taiwan University, 2008). The Japanese plan was to construct the Kaoping Delta as a twin-core intercity structure: Kaohsiung Port was one core as an export harbour, while Pingtung City was the other core for distributing agricultural products in the Kaoping Delta. This plan would integrate the whole delta as the hinterland of Kaohsiung Port. The transportation system was designed according to this twin-core structure. The roads around Kaohsiung Port were laid out in a grid system, with the main roads leading towards the port area. Although the design of roads was also based on grid system, there were four grid systems along five directions connecting downtown Pingtung with the surrounding cities, in order to collect agricultural products more efficiently (Figure 3). Finally, in 1908 a railroad



Source: Re-drawn by author; original source from Academia Sinica (2010)

Figure 2.
The natural form of the surface water context of the Kaoping River in 1895 as a braided river



Source: Re-drawn by author; original source from Taiwan DTM, Ministry of Economic Affairs; Academia Sinica (2010)

Figure 3.
The twin-core intercity structure of the Kaoping Delta during Japanese colony (1895-1945)

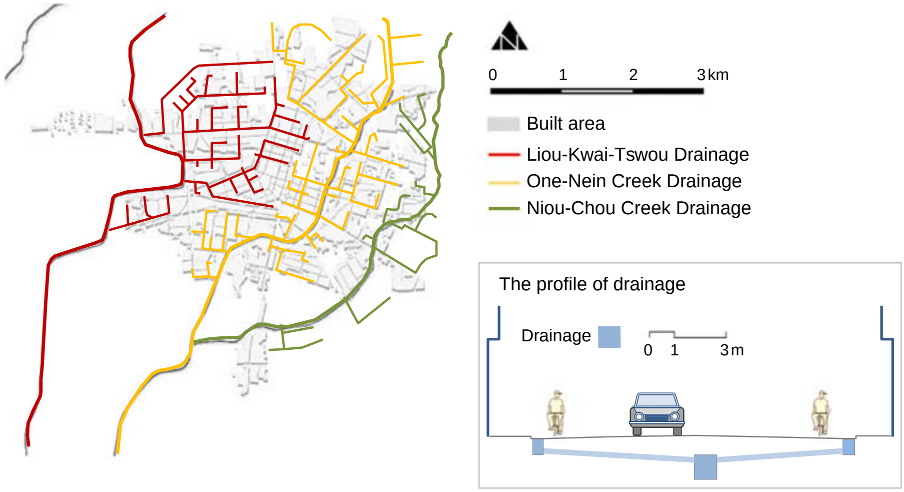
connected these two different grid systems into a holistic structure. This spatial structure needs the protection of the dike system, while floods are the constant threats to the Kaoping Delta. Two serious inundations in 1920 revealed the weaknesses of this area. A new dike system was completed in 1938 which further forced the water flow northwest directly into the main branch of the Kaoping River (Chen, 1993).

3.3 Occupation layer

The grid system was a good concept for the goals of the colonial government, to develop a city with very efficient logistics and a flexible pattern that ensures cost- and time-effective expansion potential. The grid roads for the export port were pointed directly towards the piers to maximize the efficient delivery of goods. The Japanese enacted the A-hou, the old name of Pingtung, City Plan in 1913 dividing downtown into six districts mainly along the main traffic roads as a radial-grid pattern for maximum efficiency in collecting goods. Logistics efficiency was rapidly enhanced by this spatial pattern (Pingtung Government, 1991). This radial-grid street pattern has dominated the arrangement of urban drainage. The over-land flow of storm water through this area is drained into three main drainage channels, Niou-Chou Creek Drainage, One-Nein Creek Drainage and Liou-Kwai-Tswou Drainage, by the radial-grid drainage (The Seventh River Management Office, 2010) (Figure 4).

3.4 Flood problems due to extreme storms and very dense urbanization

According to the result simulated by the hydrodynamic 2D Overland Flow simulation module of SOBEK (Deltares, 2010) based on the precipitation data of Kalmaegi Typhoon in 2008, some areas will be flooded (Figure 5) (The Seventh River Management Office, 2010). This simulation result could be further verified by the information of flood areas from 2006 to 2010, which illustrates the impact of the radial-grid street on the flood patterns in Pingtung City. The flood risk significantly increases when the storm water runoff flows along the grid street and accumulates in



Source: Re-drawn by author; original source from The Seventh River Management Office (2010)

Figure 4.
Left: three major drainage systems mainly built along the grid urban block system; right: the profile of drainage system in Pingtung City

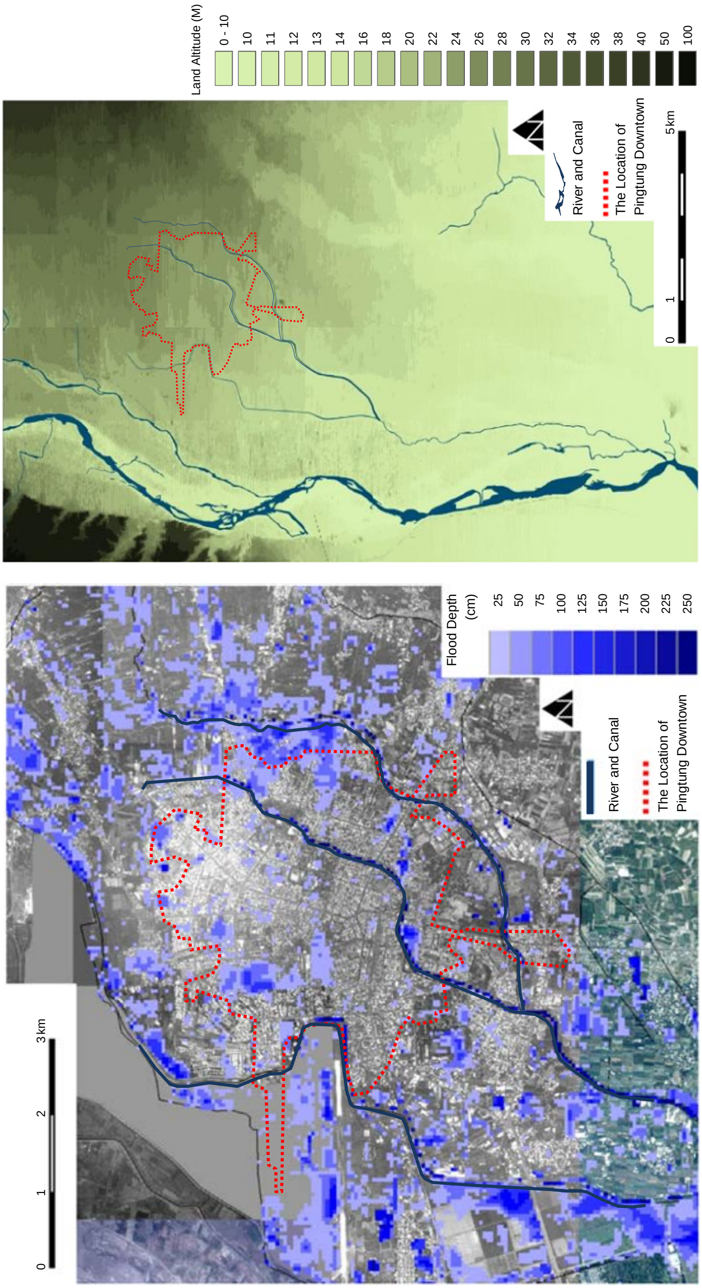


Figure 5.
Left: the simulation of flooded areas by the hydrodynamic 1D (Channel Flow)/2D (Overland Flow) simulation module of SOBEK[a]; right: the topography around the Pingtung downtown[b]

Source: [a]The Seventh River Management Office (2010); [b]re-drawn by author; original source from Taiwan DTM, Ministry of Economic Affairs the certain areas (Figure 6) (Pingtung Government, 2007; The Seventh River Management Office, 2010; Dawa News, 2010).

The relationship between flood areas and the urban grid structure are as follows.

Area A: the over-land flow of storm water coming from northeast was blocked by urban construction. The blocked storm runoff then changes its path and flows directly into the One-Nein Creek or the Sa-Sir Creek. Floods occur in these areas when storm water volumes exceed the designed capacity of these two creeks, e.g. in 2006, 2007 and 2010.

Area B: when the storm water runoff flows along the radial-grid structure into downtown, it becomes easily congested at the intersections of four grid systems and floods around the centre of downtown, e.g. in 2007 and 2008.

Area C: when the original path of the Chong-Lan-Zwin Canal was changed in order to bypass the airport, it created a sharp curve. The excess storm water easily gets congested at this point and paralyzes the northwester drains of the city because this channel is their only outlet, e.g. in 2006, 2007 and 2008.

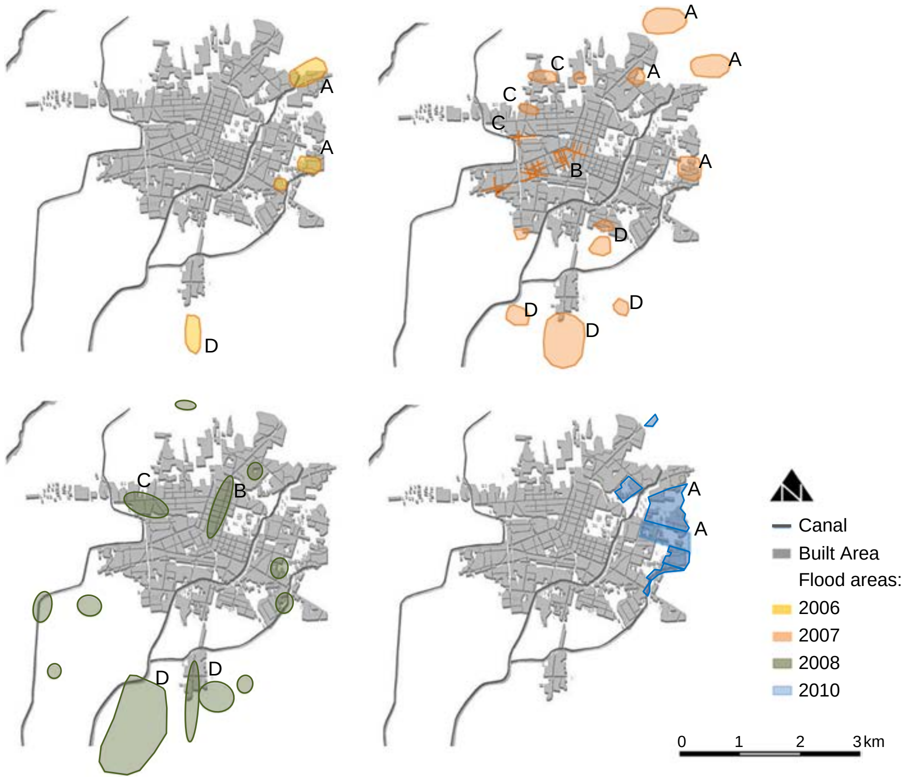


Figure 6.
The relationship between main flood areas and the urban grid structure

Notes: Four main areas: Area A – the north-eastern downtown; Area B – the central downtown; Area C – the north-western downtown; and Area D – the southern downtown

Source: Re-drawn by author; original source from Taiwan DTM, Ministry of Economic Affairs; Pingtung Government (2007); The Seventh River Management Office (2010); Dawa News (2010)

Area D: this area is the confluence of the One-Nein Creek and the Sa-Sir Creek where the excess storm water flows into the irrigation system and overflows the channel, e.g. in 2006, 2007 and 2008.

The floods in these areas are caused by the congestion of the excess storm water within the drains, not by overflow from the river, which means the capacity of the drains just with the standard for a five-year storm frequency (The Seventh River Management Office, 2010) needs to be expanded. This requires additional space; however, due to dense urbanization, the space beneath the roads is clogged up by various urban support systems, such as potable water pipes, electric cables and others (Figure 7). Rearranging these systems to find extra space for expansion of the drainage system would be difficult.

3.5 Design

Although the radial street system had helped concentrate goods to Pingtung City and transport them to Kaohsiung Port, the radial-grid spatial drainage pattern has induced unexpected congestion of storm water within downtown. However, radial system can be used not only to concentrate goods but also distribute excess storm water out of downtown. It means the roads towards to the southwest, the south and the southwest could be designed with the function of draining the excess storm water from the downtown area because the north-eastern downtown is higher than the southern, while it is difficult to extend the existing drainage system beneath the roads in the downtown area (Figure 8).

The concept of roadway drainage could be viewed as a shallow street canal system. In the past, all of the rainwater was collected in drain pipes. This new method adds the new function of water storage to the road surface. Up to a designed depth, around

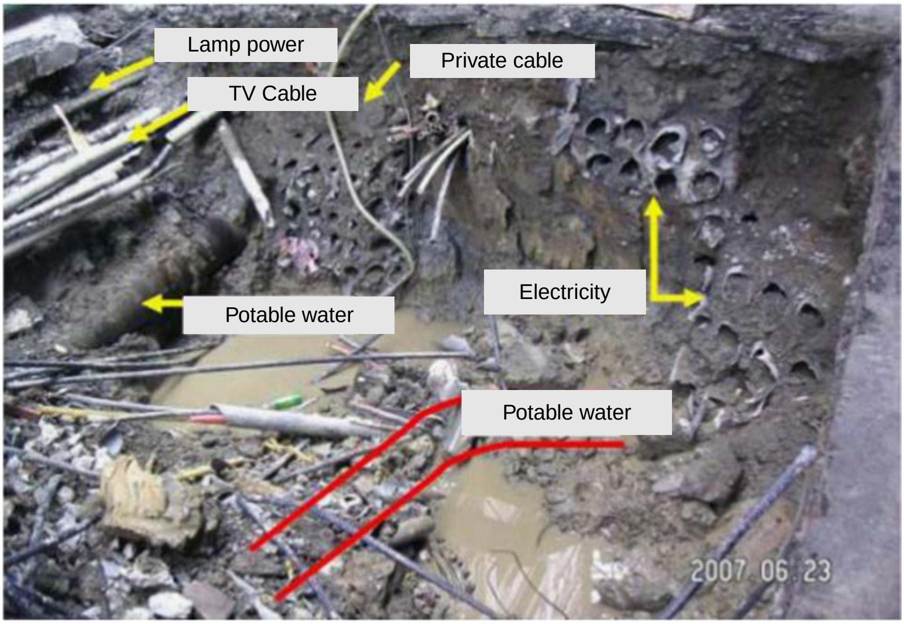
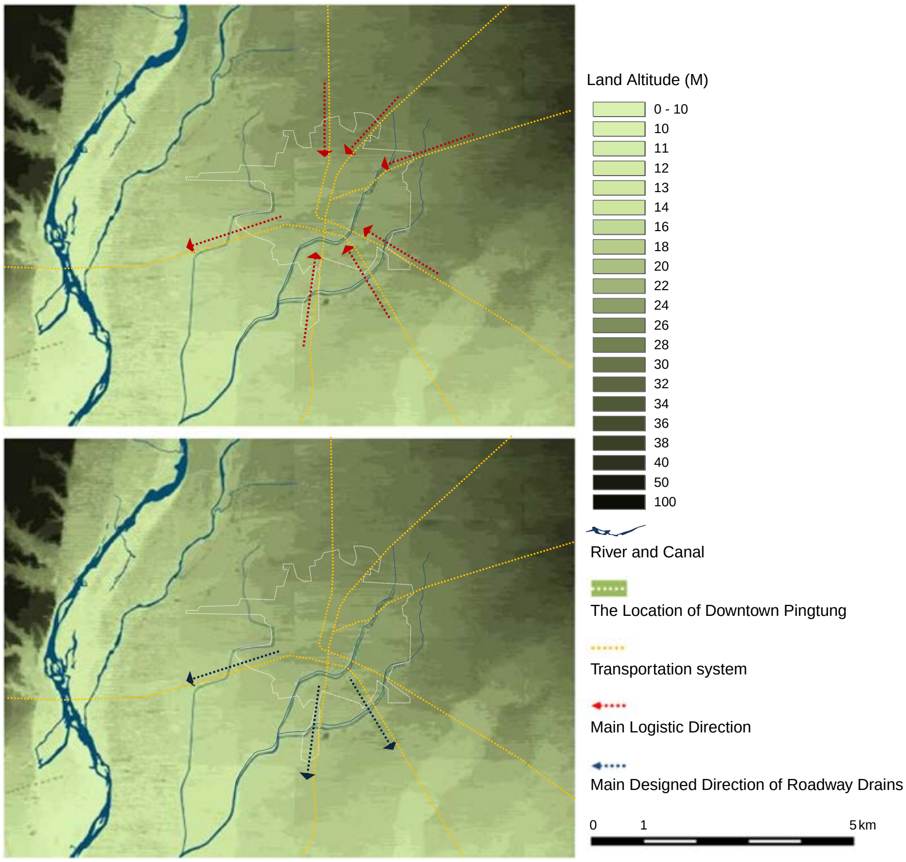


Figure 7.
The mess of various pipe systems in the downtown area beneath roads

Source: Su (2009)



Source: Re-drawn by author; original source from Taiwan DTM, Ministry of Economic Affairs

Figure 8. Two different designed concepts in one radial system: one is the function of gathering goods (red arrow); the other is of draining the unexpected storm water from the downtown area (blue arrow)

20 cm, the roads can be flooded and cars can also pass safely. The streets would function as shallow canals to channel excess water away from downtown during storms. This new drainage channel created on road surface could provide a section area of 0.2 m × W m, W is the width of road, for draining function. It is equal to about five times of the original drainage capacity of the underground drainage pipe, 1.2 m × 1.0 m pipe under a road 30 m wide (Figure 9). In fact, if this design could be applied to the major roads already equipped with drains in the downtown area, e.g. around 40 km of roads with an average width of 15 m, the total storage amount of this new design could reach 120,000 tonnes. This volume is more than twice the 58,800 tonnes that came down on the downtown area during Typhoon Bilis in 2008 (The Seventh River Management Office, 2010).

4. Discussion

Although the concept of roadway drainage is cost-effective, it could not be applied without considering some special conditions. The following tips and further improvements of this technology need to be considered.

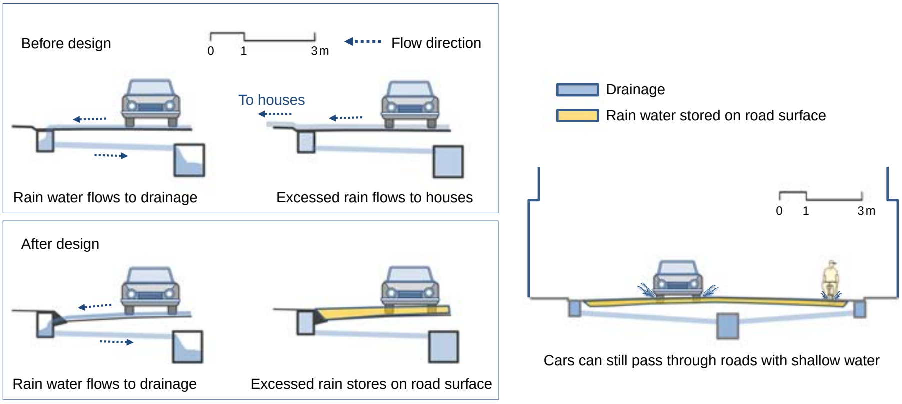


Figure 9. The design section of the roadway surface drainage

Notes: The yellow parts represent the extended areas for the drainage or detention of storm water. Created by author

First, this research is just an initial exploration from the perspective of urbanism to respond the new hydrological problems under the impact of extreme storm events, by which a further trans-disciplinary collaboration, especially between hydrology, landscape architecture and urbanism, could be promoted.

Second, the good locations for this design are where inundation results from an unexpected congestion of storm water at a relatively high elevation.

Third, a better way to apply roadway drainage is designed as an auxiliary to the original drainage system. It means the new system will not work until the original drainage has exceeded its designed capacity, which could keep the streets remaining dry after normal rainfalls.

Fourth, the design of the street drains could be combined with bike or pedestrian lanes, which would improve the quality of life in the city. For example, this new street design could combine the construction of a higher bike lane on the both sides of the street. The height differential between the bike lanes and car lane would create the new drainage space (Figure 10).

Fifth, a cost-effective way to upgrade streets with a drainage function is to apply this design together with street renewal, especially for the roads laid with asphalt which should be replaced every five to ten years. During road repair works a deeper layer can be shaved off, thus creating the drainage capacity.

5. Conclusion

Based on exploration of the interrelations between the three layers – natural landscape, infrastructure and occupation – the following three main conclusions can be drawn.

First, the radial-grid street system in Pingtung downtown, which dates back to the Japanese colonial era, has changed the natural over-land flow path of storm water and dominated the construction of the grid-drainage system. It is a big part of the problem because it congests storm water in the downtown areas.

Second, roadway surface drainage could be a cost-effective design for extending the capacity of the old drainage infrastructure if it is difficult to rearrange the complex pipe and cable systems underground or to request any requisition of private lands.

Note: Created by author

Figure 10.
The concept of street drains could be combined with the improvement plan of the urban quality

Third, this concept could be combined with other plans to improve urban spatial quality, for instance, the construction of bike or pedestrian lanes. Furthermore, the most cost-effective way is to integrate this approach with regular road maintenance and repair works.

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